Applications Development for Low-Cost Microjet Printing of Micro-Optics

FINAL PROGRESS REPORT

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by

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13. ABSTRACT (Maximum 200 words)

A novel technology was developed for fabrication of refractive micro-optical elements by inkjet printing. It is ideally suited for many optoelectronic manufacturing applications, because it is a low-cost (no masks plus an additive process), automated (data-driven), and non-contact process capable of in-situ printing of micro-optical interconnects directly onto photonic substrates and components. Optical materials, print heads and processes were developed for micro-depositing UV-curing optical epoxy formulations at high temperatures, in order to form microlenses and waveguides with dimensions down to 70 µm, which could withstand subsequent processing temperatures up to 200°C. Working with guidance from researchers at organizations such as Honeywell, Rockwell and Lawrence Livermore National Laboratories, capabilities were developed to address a wide range of next-generation photonics systems. These applications included: massively parallel, VLSI photonic switches; infrared communication systems; optical computing systems; telecom transceivers; and biochemical fiber optic sensors.

The micro-optics printing capabilities achieved and demonstrated during this contract have led to follow-on, development contracts from Honeywell (DARPA-2yrs) and Nortel Networks for datacom and telecom applications, respectively.

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1.0 STATEMENT OF THE PROBLEM

The continued evolution of information transmission and processing systems will increasingly rely on advanced micro-optical interconnect technologies to connect optically the various pieces of optoelectronic systems, in order to resolve bottlenecks resulting from high circuit density, multiple pin-outs, high data and processing rates, etc. Capabilities have been evolving for fabricating practical optical interconnects, in the form of micro-optical waveguides[1], fibers and free-space interconnects[2], between instrument backplanes, printed circuit boards (PCB's) and electro-optic components within boards.

This evolution in micro-optical interconnect technologies is being fueled by the development of new interconnect fabrication processes utilizing organic polymeric materials, which offer significant advantages over the traditional inorganic materials in both electro-optical properties and ease of fabrication.[3] Techniques which have been emerging for utilizing these materials for fabrication of free-space optical interconnects include the micromachining and melting of photo lithographically formed cylinders of photoresist[4] and the use of plastic molding methods[5]. Polymeric guided wave optical interconnects are being fabricated using photo-definition in pre-laminated sheets[6] and compression molding methods[7].

The critical issues for optical interconnects are utilization of materials and processes compatible with electronic circuit board processing and <u>low cost</u> manufacturing. In fact, the cost of fabrication and alignment of optical interconnects in advanced optoelectronic components and systems is rapidly becoming the limiting factor in reducing manufacturing costs to the levels required for expanding the market for such products and increasing the market share for U.S. producers. For example, off-the-shelf plastic and epoxy refractive microlens arrays fabricated utilizing photoresist reflow and replication to make a master array, from which duplicates are obtained by molding processes, are now becoming available for under $1K; however, prototype arrays are currently priced in the <u>$10K-$15K</u> range[8].

To address this problem, we have been developing an "Optics-Jet" technology in which refractive micro-optical interconnects may be fabricated *in situ* by ink-jet printing methods. This inkjet/microjet printing of polymeric micro-optical interconnects, as a non-contact, data-driven process, potentially could provide both significant (100-fold) reductions in costs and increases in the flexibility of manufacturing of optoelectronic packages and interconnect components, in addition to enabling new optical-interconnect device configurations. For example, this approach provides some performance advantages over competing technologies in the fabrication of high-speed microlenses and offers <u>unique</u> capabilities, such as printing microlenses directly onto the ends of optical fibers and diode laser array emitters, as well as varying the focal length of microlenses within an array and printing micro-optics on opposite sides of the same substrates.

This report summarizes our progress under this contract in developing this new technology and attracting the interests of potential commercialization partners.

2.0 PROJECT GOALS

2.1 Technical Objectives

The overall objective of this project has been to develop both the materials and printing processes to the levels required to achieve and demonstrate the capabilities for printing refractive micro-optics to the specifications required for a broad a range of optoelectronic manufacturing applications, in order to enable wide commercialization of the technology by U.S. manufacturers. The key specific technical objectives have been:

(1) Development of a set of optical materials which, firstly, have the requisite rheological characteristics required for ink-jet printing (e.g., viscosity reducible to below 40 centipoise) and, secondly, the post-cure optical properties (refractive index & transmissivity) and thermal & chemical durability (e.g., heatable to 200°C) required for commercial applications;

(2) Development of printing hardware, software and processes needed to print micro-optical configurations (microlenses, waveguides, etc.) of use to the optoelectronics industry, and to the required dimensions, tolerances, and placement accuracies.

2.2 Pre-Commercialization Objectives

The overall goal here has been to attract the interest of major U.S. optoelectronics manufacturers in potentially licensing and using this "Optics-Jet' technology in their in-house manufacturing operations. The strategy for achieving this goal has consisted of the following elements:

(1) Publishing widely our research results via conference presentations, journal articles and our website [www.microfab.com];

(2) Performing feasibility studies for micro-optics printing applications of potential end-users, with funds provided by these companies;

(3) Becoming subcontractor for micro-optics fabrication on the research projects of some of the major players in the optoelectronics industry, again, using their funds for the development work to leverage the impact of ARO dollars.

2.3 Overall Assessment of Goal Achievement

We believe that all of these objectives have been achieved or nearly achieved. We have gone from establishing feasibility for "Optics-Jet" technology to demonstrating the micro-optics printing capabilities required for many mainstream optical interconnect applications, ranging from "smart-pixel"-based optical switches, optical data storage & read-write devices, optical sensors and transceivers for telecommunications. Consequently, we have been selected as subcontractor for micro-optics fabrication on two Honeywell DARPA projects, and expect micro-optics printing technology development contracts soon from Nortel and other key players in the "telecom," "datacom" and sensor arenas.

3.0 SUMMARY OF KEY RESULTS

3.1 Materials Development

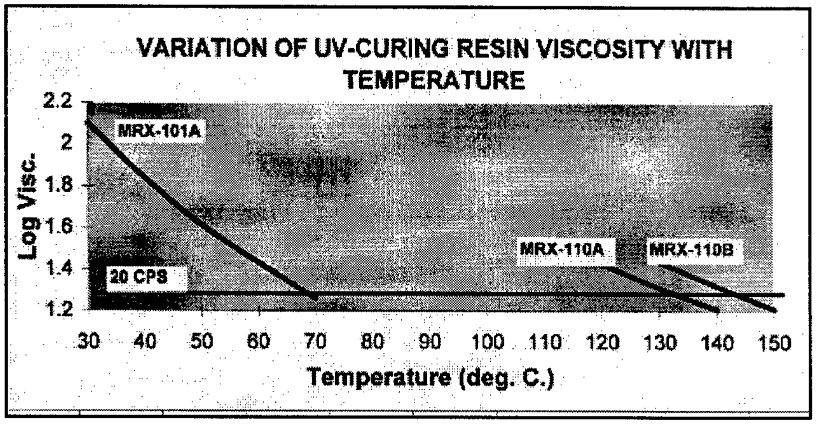

Figure 1. *Temperature dependence of viscosity for three UV-curing optical printing formulations, with microjetting temperatures indicated by crossing points of 20 centipoise line.*

Since no suitable commercial optical adhesives were available, we have developed a series of ink-jet-printable, UV-curing, optical epoxy formulations which, after curing, exhibit many of the properties required for commercial applications (such as refractive indexes close to that of glass and stability against thermal cycling up to 200°C). These 100% solids optical monomer fluids with UV-initiators were formulated over a range viscosities which were reducible to the 20 centipoise level required for drop-on-demand[9] microjetting by heating, as illustrated by the data of Figure 1. This range of room temperature viscosity levels provided a means of varying printed microlens aspect ratio (height/diameter) among lenslets with similar volumes. Working with an outside chemical contractor we also developed a set of fluids for coating optical target substrates prior to printing which reduced the wetability of the surface to the deposited material to the degree determined by the free energy of the fluid. A reduction in surface wetting reduces the spread of the deposited materials, thereby providing an additional control of the printed element aspect ratio.

The developments of these custom optical "ink" and surface modifier formulations were key accomplishments, because they enabled the printing of refractive microlenses and waveguides with a wide range of configurations, optical performance properties and durabilities, which are not as readily achievable by competing, photolithography-based, micro-optics fabrication technologies.

3.2 Microlens Printing

Utilizing these materials and the drop-on-demand microjet printing approach, we have demonstrated capabilities for printing arrays of high-speed (f# = focal-length/diameter ~ 1.0) refractive microlenses with circular[10] and non-circular (anamorphic)[11] substrate footprint. The general breadth of capabilities achieved for printing different configurations of microlenses with our UV-curing optical epoxies substrates is illustrated in the following four micrographs. An array of hemispherical microlenses printed on low-wet treated glass is shown in Figure 2. Here

each lenslet was printed by depositing multiple droplets of material at each site, then the entire array was UV-cured. The use of the low-wet coating on the substrate enabled maintenance of edge-to-edge spacings for these 355µm diameter microlenses of only 20µm. The average speed (focal-length/diameter) of these lenslets is f#=1.22, and focal length variation among lenslets in such arrays may be maintained at less than 2% standard deviation from the average value. Variations in diameters within printed arrays are typically on the order of 1%, and relative lenslet placement accuracies of +/-3µm over 3" have been achieved. *Such arrays of hemispherical microlens may be fabricated by microjet printing at higher speeds, much lower cost ($100, vs. $10,000 for prototypes), and higher-temperature durability than by photo-resist reflow lithographic processes. Accordingly this capability has attracted commercial interest for short link optical interconnects in applications such as massively parallel, "smart-pixel" optical switches.*

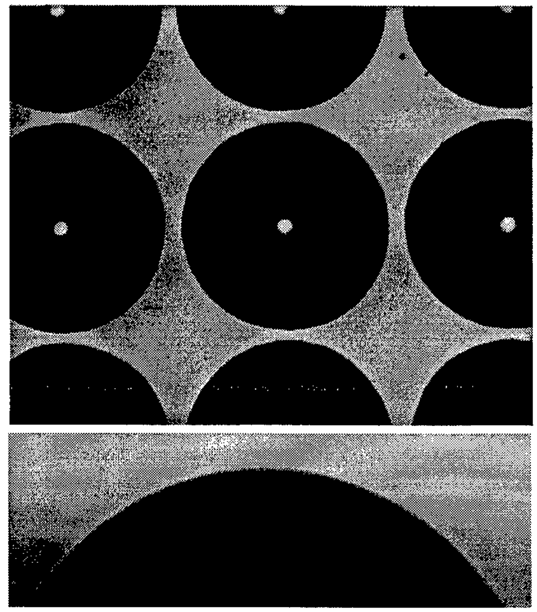

Figure 2. *Array of 355µm diameter microlenses printed on 375µm centers, shown in substrate plane (top) and in profile (bottom).*

An anamorphic microlens with a hemi-elliptical shape may be fabricated by depositing droplets (or bursts of droplets) along a line and at spacings which enable the droplets to flow together prior to curing. Here the degree of ellipticity achieved depends on volumes of deposited material and the spacings between deposition sites, as illustrated in the micrographs of Figure 3. Hemi-elliptical microlenses are of potential use in collimating the anisotropically divergent output beams of edge-emitting diode lasers, because they have two focal lengths. Light from the substrate side is first brought to a line focus by the curvature about the minor axis and, then to another, orthogonal line focus at a further distance from the substrate. *The capability for printing finely tuned hemi-elliptical microlenses which can withstand temperatures up to 200 °C has attracted commercial interest for the application of high-*

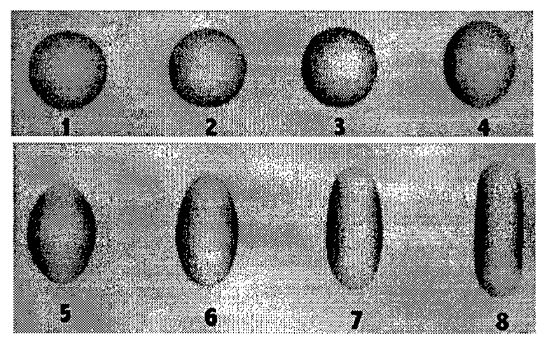

Figure 3. *Hemi-elliptical microlenses printed with six each 60µm droplets on site spacings increasing by 10µm from #1 to #8 (100X magnification).*

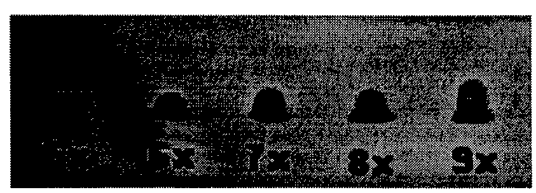

Figure 4. *Variation of microlens aspect ratio (height/diameter) by UV-light flashes between deposition of indicated number of successive 50µm droplets.*

power diode laser array coupling to optical fibers.

Microlenses may be printed with high aspect ratios and quasi-hyperbolic curvature, as illustrated in Figure 4, by stabilizing the material with an *in-situ* flash (e.g., 0.2sec) of UV-light between depositions. The objective in printing this lenslets of this configuration is to increase speed and reduce spherical aberrations. The developmental challenge for this configuration, which has not been completely overcome to date, is avoiding formation of light-scattering "skins" of higher density material at the flash cure levels.

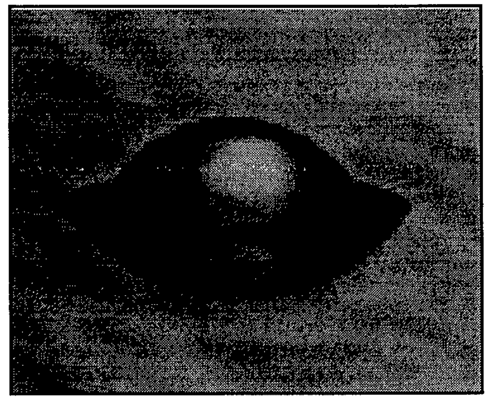

Figure 5. *Profile view of two plano-convex microlenses (top-625μm, bottom-860μm in diameter) printed coaxially on opposite sides of 160μm thick glass substrate.*

A final illustration of breadth of microlens printing capabilities achieved on this project is shown by the micrograph of Figure 5. By printing two lenslets aligned on opposite sides of the substrate, and adjusting their diameters appropriately, smaller focal spot sizes may be achieved, which are of *potential interest for read/write optical disk heads.* If the focal length of the smaller lenslet is adjusted to be at the front surface of the larger one, which has been coated with a highly reflective material, one has a "cat's-eye retro-reflector" which reflects back along the same path any incoming beam within about 60°of the axis.[12] *This double-sided printed microlens structure then becomes a device with potential use in interferometric tracking and in vehicle-to-vehicle or plane-to-plane optical communications, which cannot be readily fabricated by competing photolithographic technologies.*

3.3 Waveguide Printing

Two different methods were developed for printing multimode optical waveguides. One involves printing a linear pattern of adjacent droplets of optical material onto a substrate so as to form a hemi-cylindrical ridge structure of arbitrary configuration,[13] as illustrated by the micrograph of Figure 6. Here site spacings and the number of droplets deposited per site are adjusted to get smooth coalescence of droplets prior to solidification, and other parameters such as straight segment lengths, turning angles and numbers of "branches" are software menu driven.

Figure 6. *Portion of 1-32 branching ridge waveguide, with 116μm wide branches, printed from data file.*

Such stand-alone waveguides are easier to print using optical thermoplastics than UV-curing optical materials, due to the rapid solidification of the thermoplastics by cooling upon striking the substrate surface.

The other method of printing optical waveguides is to microjet optical material into micro-machined grooves, as illustrated by the micrograph of Figure 7. Here the grooves were filled by depositing 50μm diameter droplets into the grooves and UV-curing after the grooves had been filled. The grooved silicon wafer was first coated with Tantalum to enable removal of the waveguides by undercutting with dilute HF acid, which does not attack the UV-curing optical epoxy.

Figure 7. *60μm x 60μm cross-section waveguides fabricated by printing UV-curing optical epoxy into channels micro-machined into silicon wafer.*

3.4 Precision of Micro-optics Printing

The range of potential commercial applications for the micro-optics printing technology developed on this project will be highly dependent on the precision and reproducibility achieved in placement and formation of micro-optical elements.

To determine printing process capability for relative microlens placement accuracy, a 3" quartz wafer with a photolithographically etched grid pattern was used as a target substrate. A precision rotation stage was used to align the XY substrate stages to the grid lines, then 150μm diameter microlenses were printed in the lower right-hand corner of each of about 6,000 grid squares, as indicated in the micrographs of Figure 8. After curing, a RAM Optical vision system with automated edge-finding capability was utilized to measure the distances in X & Y of the centers of 256 each, randomly selected lenslets from the nearest grid corner. An example of the data obtained in this experiment is given in the histogram of Figure 9, which shows that *standard deviation errors in placement of individual lenslets, in arrays extending over areas up to 3" in diameter, can be held to within 4μm. Achievement of this capability was the key factor in winning a DARPA*

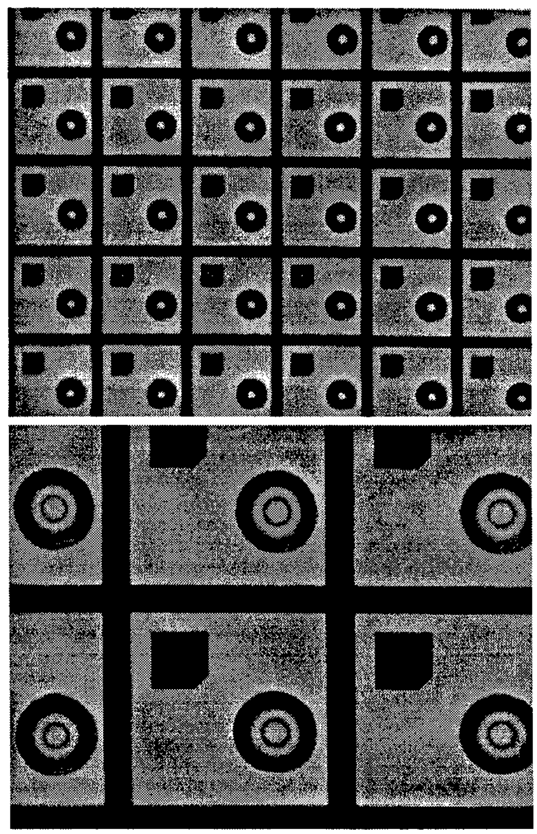

Figure 8. *Portions of an array of thousands of 150μm diameter hemispherical microlenses printed onto a 3" diameter fiducial grid substrate to measure placement accuracies.*

subcontract from Honeywell for microlens array printing for use in massively parallel optical switches (discussed in more detail in Section 4).

Two other geometric measures of precision and reproducibility in hemispherical microlens printing are diameter and focal length. An example of the capabilities in holding these parameters within a printed array to better than 2% of their average values are given in Figures 10 & 11, respectively.

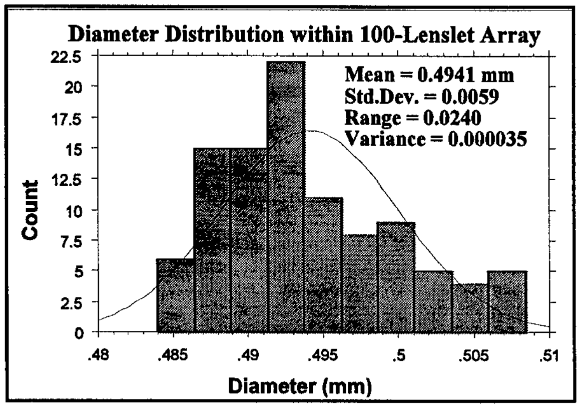

Figure 10. *Distribution of diameters of 100 each 0.5 mm diameter microlenses printed in 10x10 array on 750 μm centers, showing a typical standard deviation from the average value of 1.2%.*

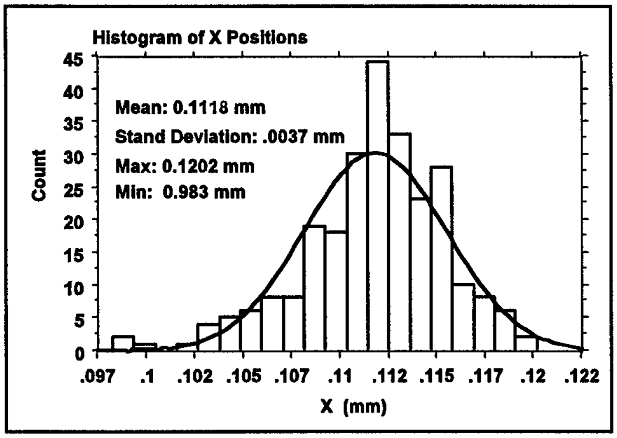

Figure 9. *Distribution of X-axis positions of center of 256 microlenses relative to fiducial grid pattern of Fig. 8.*

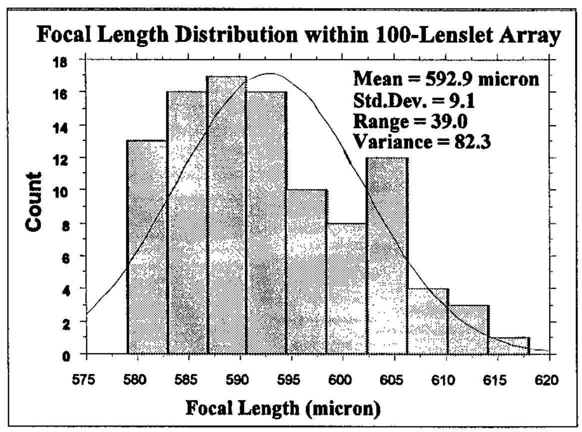

Figure 11. *Distribution of focal lengths of 100 microlens array of Fig.10, showing a typical standard deviation from the average value of 1.5%.*

Achieving this set of capabilities in microlens accuracy of placement and formation has positioned this Optics-Jet technology to address potentially many current free-space optical interconnect systems applications.

3.5 Printed Microlens Performance

The most commonly used metric of performance of a microlens in an optical system is the degree to which its focusing characteristics deviate from that of a theoretically perfect lens of "diffraction-limited" performance, i.e., with no aberrations at the wavelength of operation. The simplest way to obtain a 1st-order approximation of the aberrations of a lens is to measure its spacial power distribution in the focal plane and compare the magnitude of the full-width-at-half-maximum (FWHM) of the peak in optical energy to the theoretical value obtained with an

equivalent aperture without a lens. The extent to which the ratio of these two numbers exceeds unity provides an indication of the magnitude of spherical aberrations inherent in the lens under test. An example of this for a 105 μm diameter printed microlens is given in Figure 12, where the data were obtained with a HeNe laser source and a rotating knife edge Melles Griot Beam Analyzer located at the focal distance from the lenslet. Here the near-unity-ratio figure of merit indicates that lenslets of this size have relatively little spherical aberrations.

A much more sensitive measure of lens optical performance is the Modulation Transfer Function which is a quantitative measure of the spacial resolution achieved in imaging applications. In what is believed to be *the first measurement of MTF in* *<u>microlenses,</u>* performed by a graduate student at the University of Texas at Dallas under sponsorship of this project, it was found that spherical aberrations in printed microlenses rose rapidly with increasing lenslet size.[14] Sections of the measured MTF for 100 μm and 400 μm diameter printed microlenses are compared in Figures 13 and 14, respectively (from ref.14). By this metric relative lenslet performance is given by the Strehl Ratio (SR), i.e. the ratio of areas under the measured and theoretical curves. These data indicate a 12-fold increase in aberrations with a factor-of-four increase in lenslet size.

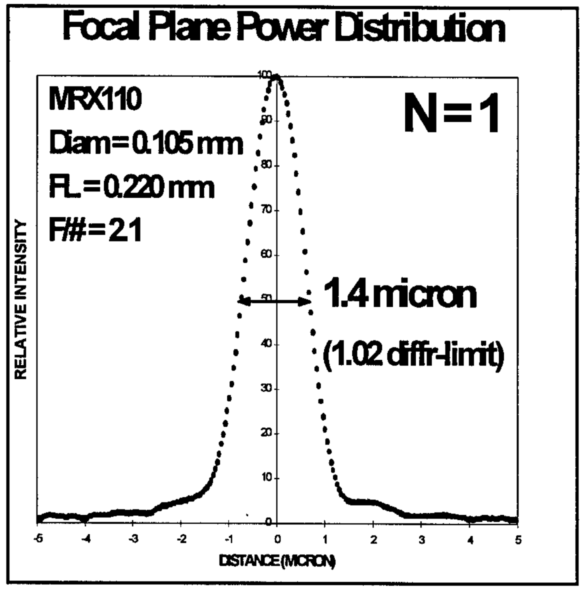

Figure 12. *Focal plane power distribution for a 105 μm diameter printed lenslet showing nearly diffraction-limited performance (ratio of FWHM actual to theoretical being 1.02).*

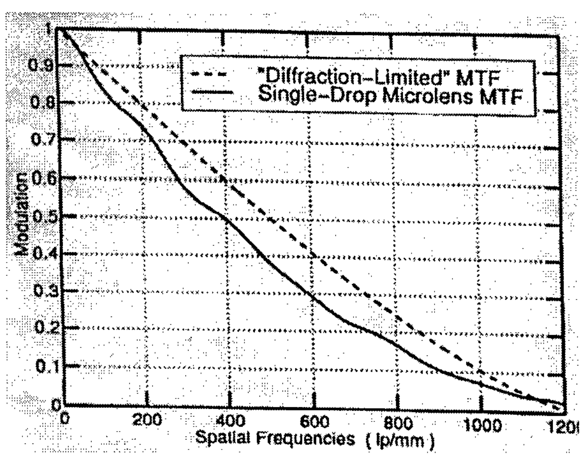

Figure 13. *Section of MTF for a 100 μm diameter microlens, giving SR=0.71.*

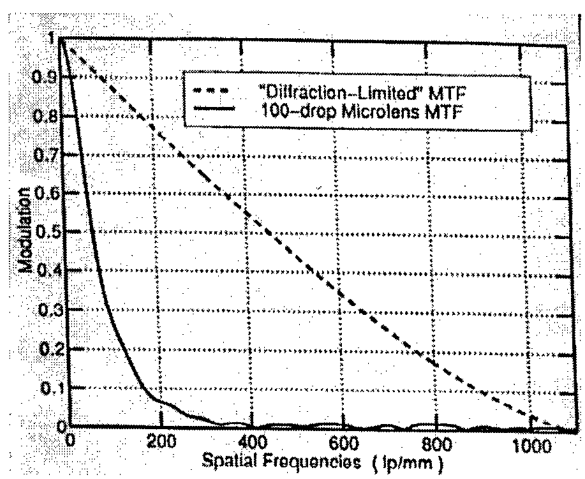

Figure 14. *MTF section for a 400 μm diameter printed microlens with SR=0.06.*

3.6 Printing of Microlenses onto Photonic Components & Devices

3.6.1 Diode Lasers

One of the applications of Optics-Jet technology explored during this project was the printing of microlenses for collimating the output beams of diode lasers. Two questions addressed in a series of experiments were: (a) what degree of collimation can be achieved for the widely diverging outputs of edge-emitting diode lasers with hemispherical microlenses, and (b) what power levels could be tolerated by these optical epoxy lenslets? Microlenses of speed f/1.2 were printed above the emitter facets of a 24-emitter, 20 Watt laser bar, as indicated in Figure 15. The lenslets were deposited onto a 125 µm thick glass plate epoxied to the bar, in order to provide the offset needed to put the back focal length of the lenslets close to the emitter facet plane. From Figure 16 it can be seen that good collimation was achieved in the widely diverging (30°) plane perpendicular to the bar. The lesser degree of collimation achieved in the parallel plane is believed to be due the back focal length of the lenslets still being behind the emitting 100 µm. After 12 hrs of burn-in with the printed lenslets at 20 Watts, the output power had dropped by only 0.3W.

It was concluded from this experiment that micro- lenses printed with our UV/200 °C-cured optical epoxy could both collimate outputs of edge-emitting diode lasers and withstand

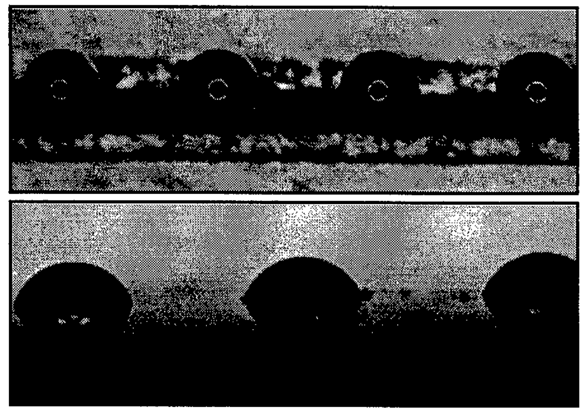

Figure 15. *200 µm diameter hemispherical microlenses printed on 390 µm centers over emitter facets of 20 Watt diode laser bar, shown in surface plane (upper) and in profile (bottom hemisphere is reflection).*

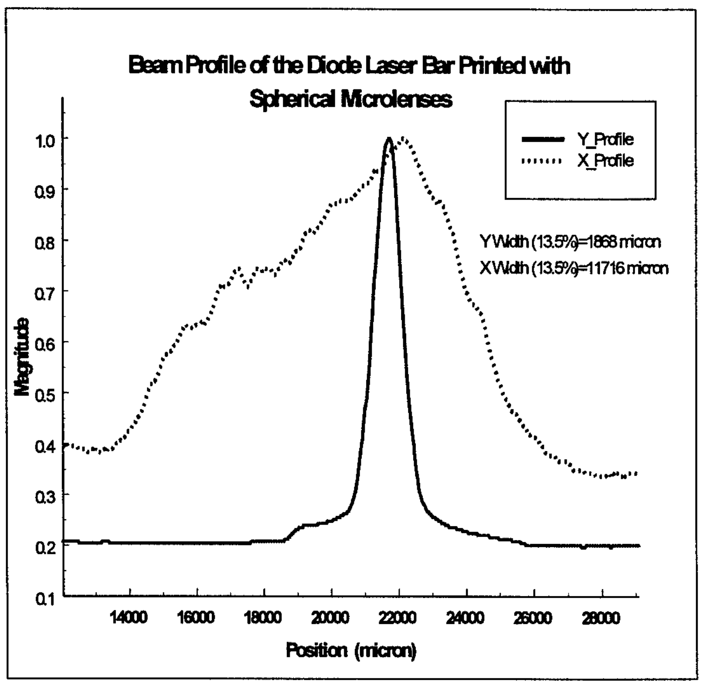

Figure 16. *Beam profiles of an emitter of diode laser bar with printed hemispherical microlens in perpendicular (solid line) and parallel (dotted line) planes.*

power levels of 1 W/lenslet.

3.6.2 Optical Fibers

Another application of Optics-Jet technology of potential wide-spread utility in tele-communications is the printing of lenslets onto the tips of optical fibers, in order to increase their numerical aperture (NA) for the collection of light from diode laser sources. Increasing the fiber NA could both increase the efficiency of power coupling and relax component alignment requirements in the manufacture of fiber optics transmitters. Here photolithographic methods and alternative techniques such as etching the ends of the fibers are impractical or much more expensive and irreproducible, respectively, than the microlens printing approach. Examples of microlenses printed onto the tips of 100µm-core, multi-mode and 10µm-core, single-mode optical fibers are given in the photos of Figures 17 and 18, respectively. For the multimode fibers the lenslets must be printed to the full diameter of the fiber cladding to affect a factor of 2-3 increase in NA, and the printed lenslet is self-aligning to the fiber by adhesion and surface tension. For a single mode fiber a much smaller microlens is required, and alignment of the lenslet to the center of the fiber becomes an important requirement for maximizing performance.

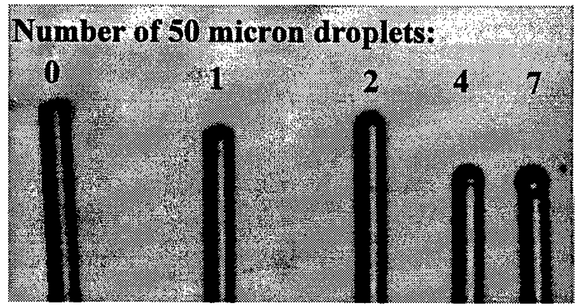

Figure 17. *Variation of curvature of lenslets printed onto the tips of multimode fibers 140 µm in diameter by varying number of deposited droplets.*

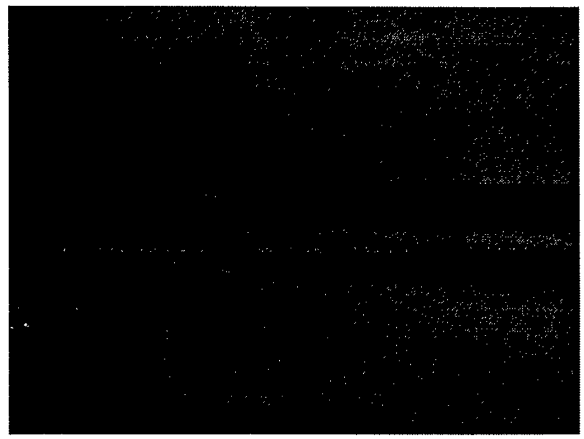

Figure 18. *70 µm diameter microlens printed onto the tip of a 125 µm diameter single mode optical fiber of 10 µm core diameter for increasing fiber NA.*

Since printing of microlenses onto the tips of optical fibers to increase NA can potentially provide significant amount of added value at very low cost in the manufacture of components such as telecommunication transmitters, our work in this area has attracted attention from optoelectronics companies such as Ericsson and Nortel.

A different application explored for microlens printing onto optical fibers is the deposition of optical epoxy containing indicator chemistries onto the tips of imaging optical fiber bundles to make biochemical optical sensors. The potential advantage which Optics-Jet technology brings to this application is the capability for precision printing of reproducible sensor elements containing different indicator chemistries onto the same optical fiber bundle. In an initial experiment a pattern of seven each 80 µm diameter hemispheres of optical epoxy

containing fluoresceine dye were printed onto the tip of a 480 μm diameter bundle of several thousand optical fibers, as in Figure 19. Here the fiber is illuminated with UV-light and the individual fibers within the bundle can be discerned beneath the printed, fluorescing lenslets. In a sensor application the illumination and detection is performed at the other end of the fiber bundle and the intensity of fluorescence of the indicator contained in each hemisphere would vary with level of parameter under test, e.g., pH or O2 level. Tests of printed fiber bundles by Lawrence Livermore National Laboratories, who supplied the fibers and paid for most of our work, indicated fiber-to-fiber and hemisphere-to-hemisphere variations in fluorescent intensity on the order of only 5%. *This result suggest that Optics Jet technology could provide a method for fabrication of low cost optical fiber biochemical sensors, which is potentially many-fold more precise, reproducible and lower in cost than current state-of-the-art techniques,* [15] *and which has applications ranging from clinical diagnosis and manufacturing process control to biochemical warfare defense systems.*

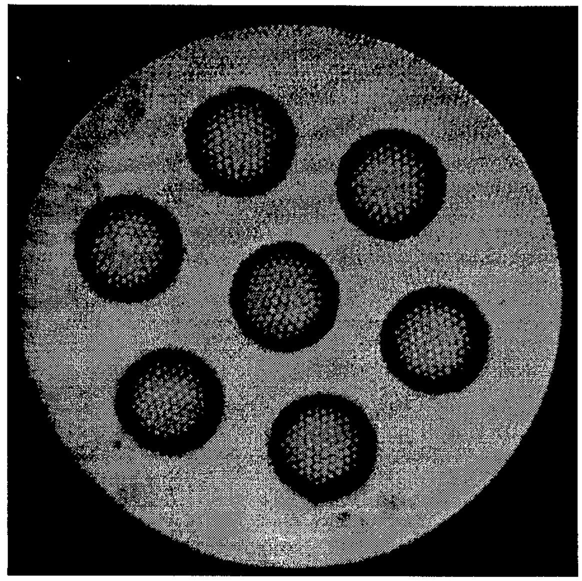

Figure 19. *Pattern of 80 μm diameter hemispheres of fluorescing optical epoxy printed onto the tip of a 480 μm imaging fiber bundle for a biochemical sensor.*

3.6.3 Macro-lenses

Another application for Optics-Jet technology is printing of microlenses onto macro-lenses (diameter > 3mm) to enhance optical coupling efficiency. An example with which we experimented is printing arrays of microlenses onto the tips of gradient index of refraction (GRIN) rod lenses for use in an optical-thyristor[16]-based, data-transcription system[17] with potential applications in optical computing[18] *By printing an array of microlenses onto the tips of the GRIN rods, as exemplified in Figure 20, the optical efficiency of such systems can be increased theoretically by up to a factor-of-six,*[19] *which translates into*

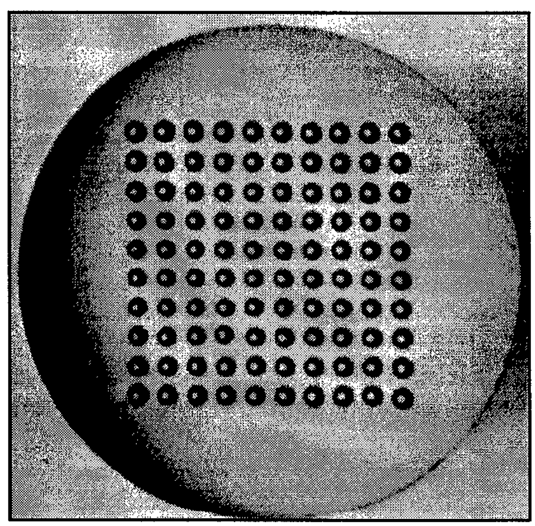

Figure 20. *Array of 220 μm microlenses printed onto end of a 5mm diameter GRIN lens rod to enhance efficiency of optical coupling.*

an even greater increase in system switching speed

3.6.4 Smart Pixels

Another application of microlens printing which has been demonstrated during this contract period include the printing of large arrays of microlenses on quartz substrates to provide, potentially, free-space optical interconnects in VCSEL (vertical-cavity surface-emitting laser) smart-pixel-based[20], massively parallel photonic switches for data communication. An example of such a microlens array is shown in Figure 21, where the optical interconnect for unit cell for each pixel consists of two adjacent microlenses, one each for collimating the output beam of a VCSEL and the other for focusing an input beam into the adjacent photodetector. A total of 37 chips were printed on a 3" wafer for this initial experiment with each chip consisting of two interlaced 16x16 arrays, giving a total of 19,000 each lenslets. *In this application Optics-Jet technology is the lenslet fabrication of choice over photolithographic methods from both interconnect efficiency and thermal durability perspectives.*[21] (Diffractive microlenses cannot match the speed/focusing-power of refractive lenslets and the photoresist used for refractive microlens fabrication cannot withstand the 200°C soldering steps involved in assembling the switch.)

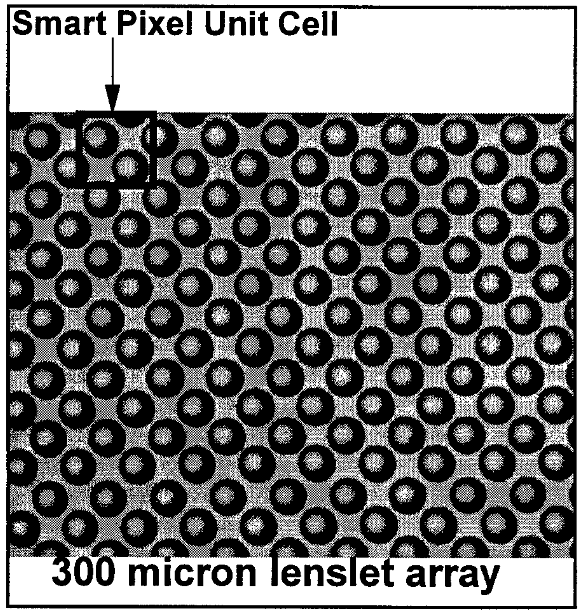

Figure 21. *Portion of two interlaced arrays of 16x16 each 300 μm diameter printed microlenses, with two adjacent lenslets for each smart pixel.*

4. PROGRESS TOWARD COMMERCIALIZATION / PHASE-III-CONTRACTS

Major companies with U.S. operations who have expressed interest to date in this Optics-Jet technology developed in part under this contract include: Honeywell, Nortel Networks, Ericsson USA, Emcore/MODE, MCI WorldCom, Rockwell, AMP, Alcatel, Seagate, Texas Instruments, Eastman Kodak, Polaroid, ADC Telecom, Compaq Computer, Abbott Laboratories, Lucent Technologies, Opto Power, Lasertron, Motorola and Phillips.

The companies and organizations who have hired MicroFab to perform short feasibility studies for applying Optics-Jet to their applications of interest include:

1. Honeywell (3 projects)

2. Rockwell (2 projects)
3. Lawrence Livermore National Laboratories (2 projects)
4. Nortel Networks (3 projects)
5. Free University of Brussels (1 project)

The biggest current opportunity for continued development and eventual commercialization of the technology developed on this project is a two-year, $165,000 sub-contract awarded to MicroFab by the Honeywell Technology Center (HTC), the prime contractor on a multi-company DARPA project, entitled "VCSEL-based Interconnects in VLSI (very large scale integration) Architectures for Computational Enhancement." MicroFab's role in this project is to print large arrays of precisely placed microlenses (as in Fig. 22) for use in a massively parallel (1024 ins & outs), reconfigurable optical switch for high-speed data transcription between microprocessors. Additional development work will be required to meet Honeywell's ultimate device performance goals under this HTC subcontract, *so this new project could be considered to be a "Phase III" extension of the completed ARO contract.*

Honeywell has also identified additional potential applications for this Optics-Jet technology in other categories of products currently under development at HTC, which include printing of microlenses onto VCSEL wafers for beam collimation and "next-generation" data storage and optical sensing devices.

Finally, MicroFab has just made the semifinals of a NIST (National Institute of Standards & Technology) Advanced Technology Program competition with a three year proposal designed to develop the additional micro-optics printing capabilities (3X smaller lenslets & greater printing precision) needed for high-end commercialization of Optics-Jet technology, with a number of the above listed companies participating as end-user partners.

5. CONCLUSIONS

The various capabilities for ink-jet printing of micro-optics achieved under this contract have opened up a number of application areas in the optoelectronics manufacturing arena which could potentially be addressed to significant current advantage by the Optics-Jet technology, as concluded by researchers in companies such as Honeywell, Nortel and Rockwell (who could potentially provide commercialization paths for it). These capabilities, illustrated at length above, may be summarized as follows:

1. Printing of refractive microlenses with speeds (focal-length/diameter) down to 1.1;
2. Variations in printed lenslet diameter and focal length within an array of less than 2%;
3. Placing micro-optical elements onto target substrates with accuracies better than 4μm;
4. Thermal durability of printed microlenses up to 200°C;
5. Printing of microlenses onto tips of optical fibers and onto diode laser sources.
6. Printing of non-spherical elements such as hemi-elliptical microlenses and waveguides.

These micro-optics printing capabilities developed during the ARO contract performance period have not only attracted the interest of key photonics development and manufacturing organizations, but have also resulted in nearly $200,000 (extending over the next two years) in subcontracts to develop further and explore utilization of this technology for specific applications, thereby leveraging the Government dollars supporting this contract.

In summary, this SBIR Phase II contract has enabled the development of a new technology for micro-optics fabrication by ink-jet printing, which has the dual potentials for both reducing significantly the cost of optoelectronics manufacture and for enabling the fabrication of new and more efficient photonic device architectures not readily achievable with alternative state-of-the-art optical fabrication methods. The cost reductions will accrue largely via automation in optoelectronic package assembly, where the aligning and bonding of micro-optics to optical sources and detectors are generally time-consuming, manual operations which often constitute the largest cost component of the manufacturing process. The new device architectures enabled will utilize the capabilities for the automated, non-contact printing of micro-optics onto any component or device. If this Optics-Jet technology is commercialized by leading-edge photonics manufactures such as Honeywell, the dual-use benefits accruing in both potential benefit-areas will contribute to making American photonics manufacturing more competitive in world markets, thereby helping the U.S. economy and reducing the dependence of the U.S. military on imported photonic devices.

6. LIST OF PUBLICATIONS & TECHNICAL REPORTS

Publications, technical reports presented at conferences and a masters degree thesis, which were based, at least in part, on work performed under this contract include:

[1] W.R. Cox, D.J. Hayes, T. Chen and D.W. Ussery, "Fabrication of Micro-optics by Micro-jet Printing," *SPIE Proceedings* Vol. 2383, pp. 110-115, 1995.

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[3] W.R. Cox, D.J. Hayes, T. Chen, D.L. MacFarlane, H-J. Trost and R.F. Hoenigman, "Micro-jet Printing of Microlenses," *Proceedings, OSA Annual Meeting*, invited paper #I-0095, Rochester, NY, Oct., 1996.

[4] W.R. Cox, T. Chen, D.J. Hayes & R.F. Hoenigman, "Microjet Printing of Optical Waveguides," *IEEE Laser and Electro-Optics Society 1996 Annual Meeting*, Nov. 18-21, 1996.

[5] W.R. Cox, "Microjet Printing of Micro-optics and Solder Balls for Optoelectronic Manufacturing and of Other Materials for Biomedical Applications," invited seminar presented to the *Honeywell Technology Center*, Minneapolis, MN, Aug., 1997.

[6] W.R. Cox, "Low-Cost Optical Interconnects by Microjet Printing," invited seminars presented to the North Texas and Austin Texas *Local Chapters of IMAPS* during 1997.

[7] W.R. Cox, D.J. Hayes, T. Chen, H-J. Trost, M.E. Grove, R.F. Hoenigman and D.L. MacFarlane, "Low Cost Optical Interconnects by Micro-jet Printing," *ISHM 29th International Symposium on Microelectronics*, Minneapolis, MN, Oct., 1996; also *IMAPS International Journal of Microcircuits & Electronic Packaging*, Vol. 20, No. 2, pp.89-95, 1997.

[8] Brian T. Teipen, "Microlens Characterization using the Modulation Transfer Function," *masters thesis*, Dept. of Electrical Engineering, The University of Texas at Dallas (unpublished), Aug., 1997.

[9] W.R. Cox and M.E. Grove, "Ink-jet Fluids Development for Manufacturing Applications," invited seminar presented to the Chemistry Department of the *University of Texas at Dallas*, Richardson, TX, Feb., 1998.

[10] D.J. Hayes, "Micro-Jet Printing of Polymers for Microelectronic Applications," *Eight Meeting of The Dupont Symposium at Winterthur on Polymers in Microelectronics*, May 18-20, 1998.

[11] W.R. Cox, T. Chen, C. Guan, D.J. Hayes, R.E. Hoenigman, B.T. Teipen and D.L. MacFarlane, "Micro-jet Printing of Refractive Microlenses," *Proceedings, OSA Diffractive Optics and Micro-optics Topical Meeting*, invited paper #I-00002, Kailua-Kona, HW, June, 1998.

[12] D.J. Hayes, W.R. Cox and M.E. Grove, "Micro-Jet Printing of Polymers and Solder for Electronics Manufacturing," *Adhesives in Electronics '98: 3rd International Conference on Adhesive Joining & Coating Technology in Electronics*, Binghamton, NY, Sept. 27-30,1998.

[13] M. Grove, D. Hayes, R. Cox, D. Wallace, J. Caruso, M. Hampden-Smith, T. Kodas, K. Kunze, A. Ludviksson, S. Pennino and D. Skamser, "Color Flat Panel Manufacturing Using Ink Jet Technology," *Proceedings, Display Works '99*, San Jose, Feb., 1999.

[14] D.J. Hayes, W.R. Cox and M.E. Grove, "Low-Cost Display Assembly and Interconnect Using Ink-Jet Printing Technology," *Proceedings, Display Works '99*, San Jose, Feb., 1999.

[15] D.J. Hayes, M.E. Grove and W.R. Cox, "Development and Application by Ink-Jet Printing of Advanced Packaging Materials," Best Paper of Session Award at *IMAPS International Symposium on Advanced Packaging Materials: Processing, Properties &*

Interfaces, Chateau Elan, Braselton, Georgia, March 14-17, 1999.

[16] D.J. Hayes, D.B. Wallace and W.R. Cox, "MicroJet Printing of Solder and Polymers for Multi-Chip Modules and Chip-Scale Packages," *Proceedings, IMAPS International Conference on High Density Packaging and MCMs*, Denver, April 1999.

7. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

Scientific personnel from MicroFab Technologies participating in this project were:

1. W. Royall Cox, Ph.D. (Project Principal Investigator)
2. Donald J. Hayes, Ph.D
3. Hans-Jochen Trost, Ph.D.
4. Ting Chen, Ph.D.
5. Chi Guan, M.S.

Scientific participants from our subcontractor for printed optics characterization at the University of Texas at Dallas included:

6. Duncan L. MacFarlane, Ph.D (Prof. of Electrical Engineering)
7. Vishwah Nararayan, Ph.D (worked as graduate student; now at Ericsson)
8. Jim Tatum, Ph.D. (worked as graduate student; now at Honeywell)
9. Brian Teipen, M.S. (worked as graduate student; now working on Ph.D.)

8. REPORT OF INVENTIONS

"Method for Producing Micro-optical Components," U.S. Patent # 5,707,684 (issued Jan 13, 1998; filed Feb28, 1995)

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